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RESISTOJET WASTE METHANE UTILIZATION IN MANNED SPACE APPLICATION*

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Abstract

The utilization of waste gases from the environmental control/life support subsystem (ECLSS) in a low-thrust resistojet can significantly reduce spacecraft logistics requirements. Further integration with the reaction control subsystem (RCS) can also reduce the types of consumable required, thereby simplifying the logistics. This paper presents the results of a study to optimize this integration for a 50-man space base in earth orbit. The selected system utilizes biowaste methane from the ECLSS in a resistojet to decrease propellant logistics. The selection of an oxygen/hydrogen bipropellant RCS, utilizing excess hydrogen from the ECLSS with oxygen/hydrogen obtained from water electrolysis, simplifies the logistics problem by reducing the types of fluids and spares required. Also discussed is the possibility of additional resupply savings through utilization of gases from waste processing. Continuous versus intermittent operational modes of the resistojet are discussed, and sizing requirements of resistojet subsystem are defined.

Introduction

As manned space vehicles become larger and flight durations are measured in years rather than in days or weeks, new approaches to meeting subsystem requirements must be found. In order to minimize resupply and/or initial loading requirements, it is necessary to direct special attention to subsystem relationships, with emphasis on methods by which the various elements can be made to complement each other. Examination of the environmental control/life support and propulsion systems reveals that incorporation of a resistojet thruster utilizing biowaste products as propellant has considerable potential in the area of control-moment gyro (CMG) desaturation and orbit-keeping functions.

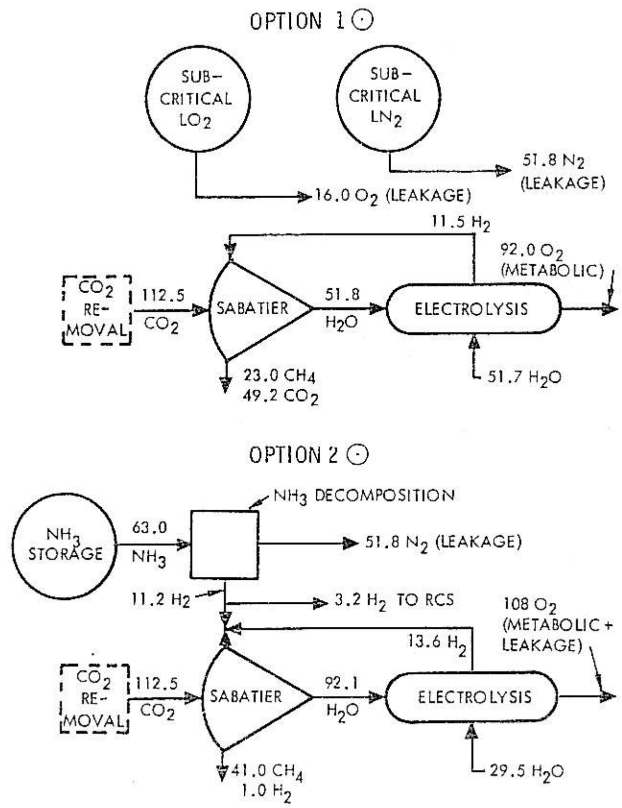
This paper presents the results of a study for the integration of the reaction control subsystem (RCS) and the environmental control/life support subsystem (ECLSS) of a 50-man space base in low earth orbit (270 nautical miles). Waste gases are available as a by-product of the reduction of metabolic carbon dioxide (CO_2) in a Sabatier reactor to recover the oxygen (O_2). Several methods of processing on-board trash also result in waste gases. The Sabatier process produces waste methane (CH_4) with either CO_2 or hydrogen (H_2) residuals for propulsion utilization. The waste gases available from trash processing depend to a large extent on the processing method. Typical gases are mixtures of methane, carbon dioxide, nitrogen (N_2), hydrogen, and water.

Propulsion functions may require larger thrusts than can be provided by the resistojet because of power limitations. In these cases, the methane and/or hydrogen available from the ECLSS can also be used as a fuel with oxygen (or other oxidizer) in a bipropellant gas thrustor. The purpose of the study was to determine the optimum utilization of the waste gases available for propulsive functions.

ECLSS Oxygen Recovery

For purposes of the paper, ECLSS/RCS integration in the oxygen recovery area will be limited to CO_2 reduction by the Sabatier process and variations in the cabin atmosphere leakage makeup approach. In past studies,(3) consideration was also given to an open ECLSS system with no oxygen recovery and to options with the Bosch process where no usable waste products are available. The results of these other ECLSS options have shown the Sabatier process to have the highest integration potential. The no-oxygen recovery case tends to have high fixed and resupply weight. In the case of Bosch CO_2 reduction, there are no usable by-products available, and additional power is required for the reduction reaction. The combination of additional power requirements and lack of waste products made the Bosch option unattractive from an integration standpoint.

A number of ECLSS options utilize Sabatier CO_2 reduction. The variables are the completeness of CO_2 reduction (hydrogen availability) and method of cabin leakage makeup. Two options which span the operating range are shown in Figure 1.



NOTE: ALL NUMBERS REPRESENT POUNDS PER DAY

Figure 1. ECLSS Options

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Since all concepts require some method of CO_2 removal, it is not considered a variable and will not be indicated in the weights to follow.

Option 1 considers a Sabatier and electrolysis approach for production of metabolic oxygen. All cabin leakage makeup is supplied by subcritical cryogenic storage. As indicated, the production of only metabolic oxygen provides insufficient hydrogen to complete the reduction of all CO_2 available. Therefore, both CH_4 and CO_2 are available to RCS.

In Option 2, the nitrogen leakage makeup by subcritical liquid nitrogen (LN_2) is replaced by an ammonia (NH_3) decomposition approach which also provides hydrogen for the Sabatier reaction. Metabolic oxygen and oxygen for cabin leakage makeup are both provided by electrolysis. The ammonia decomposition produces more hydrogen than required by the Sabatier reactor. This excess hydrogen can be provided directly to the RCS as shown or can be piped through the Sabatier reactor and mixed with the methane waste gas. Reaction of all the carbon dioxide requires approximately 5-percent excess hydrogen so that some hydrogen is always dumped with the methane with this option.

The physical characteristics of the two options are given in Table 1. As the table shows, Option 1 has the heavier fixed and resupply weight but produces a larger quantity of waste gases for RCS utilization and requires less power than Option 2. For the space base, power required was not considered to be a strong selection driver. Therefore, selection of one concept over the other was based on the utilization of the biowaste gases to reduce the overall vehicle weight and resupply by reducing RCS propellant requirements. At 2000 R gas temperature, the specific impulse of the CO_2/CH_4 mixture in a resistojet is 185 pound-second per pound; for the CH_4/H_2 mixture, the specific impulse is 290 pound-second per pound. The total impulse available for RCS, therefore, is 2.40×10^6 and 2.36×10^6 pound-second per 180 days, respectively. This would result in a negligible difference between fixed and resupply weight of the RCS utilizing gases from Option 1 compared to Option 2. Therefore, the ECLSS characteristics are controlling, and Option 2 was selected for further study.

Table 1. ECLSS Option Summary

Option 1	Option 1	Option 2
Dry weight (lb)	3,400	2,800
Resupply (lb/180 days)	21,510	16,650
Average power (watts)	11,100	15,050
Waste gas available (lb/180 days)		
CO_2	8,856	-
CH_4	4,140	7,380
H_2	-	756
Total	12,996	8,136

ECLSS/RCS Integration

The gases available from the ECLSS Option 2 may be used as (1) the propellant in a low-thrust engine such as a resistojet, (2) the fuel for a higher thrust bipropellant rocket engine, or (3) a combination of both. The optimum utilization of these gases depends on the thrust levels and engine duty cycles required to accomplish the various RCS functions.

For the space base study, the RCS provides the forces required to (1) overcome torques induced by various program elements docking to the base, (2) desaturate the control-moment gyroscopes, and (3) offset aerodynamic drag to maintain orbit altitude. Table 2 gives the total impulse requirements for a 180-day resupply period, the desired thrust levels, and the duty cycle for these functions.

The gases available from the ECLSS CO_2 management assembly are CH_4 and H_2. These gases can be provided either separately or combined, with the CH_4 always containing a small amount of H_2. These gases may be utilized in the following ways:

1. All of the ECLSS gases are used in a resistojet with an independent medium-thrust system to provide control of docking disturbance torques and to furnish the impulse requirements in excess of the waste gas capability.

2. CH_4/H_2 is used in the resistojet system, and the excess H_2 is used to augment the H_2 fuel in a water electrolysis medium-thrust system.

3. This utilization option is the same as Option 2, except the CH_4/H_2 mixture is used as the fuel with oxygen from electrolysis for the medium-thrust system. Excess H_2 from ECLSS and the RCS electrolysis is used in the resistojet.

Table 2. RCS Functional Requirements

Function	Thrust Range (lb_f)	Total Impulse (lb-sec/180 days)
Docking disturbance	10-50	3600
CMG desaturation	0.10-50	2.66×10^{-6}
Orbit maintenance	0.10-50	0.84×10^{-6}
Total	-	3.50×10^6

In all cases, the medium-thrust system utilizes electrolysis to reduce spacecraft development costs and to obtain the maximum commonality of hardware and fluids required.

The characteristics of these three options are given in Table 3. As can be seen, there is no significant difference between the options. Option 3 has the possible disadvantage of carbon particles in the exhaust plume of the medium-thrust engine. This could contaminate thermal-control coatings or experiment windows. This problem would also exist in the resistojet if the

Table 3. ECLSS/RCS Integration Characteristics

Concept No.	Thrust Level	Propellants (lb/180 Days)	Total Impulse (10^6 lb-sec)	Dry Weight (lb)	Resupply Water (lb/180 Dsys)	Power (kw)
1	Low	7,380 CH_4 756 H_2	2.36	970	3,400	2.20
	Medium	3,022 O_2 378 H_2	1.14			
2	Low	7,380 CH_4 180 H_2	1.99	1,091	3,114	2.16
	Medium	2,768 O_2 922 H_2	1.51			
3	Low	6,260 CH_4 1,087 H_2	2.32	1,055	3,225	3.13
	Medium	2,867 O_2 1,120 CH_4 27 H_2	1.18			
Medium-thrust O_2/H_2 electrolysis system			3.50	2,500	10,600	6.8
Low-thrust resistojet, NH_3 (4000 R)			3.50	1,040	940	3.1

gas temperatures exceeded approximately 2000 R. Option 2 was chosen over Option 1 primarily because the lower oxygen/hydrogen ratio of 3:1 in the medium-thrust system results in a lower combustion temperature. This should aid in designing a long-life thrust chamber.

Also presented in Table 3 are the characteristics for a single RCS system (either medium or low thrust) to accomplish all the functions. This assumes that docking impulses, for an all resistojet subsystem, would be taken out by the docking vehicle. This shows the significant advantage of utilizing the biowaste gases.

ECLSS Waste Processing

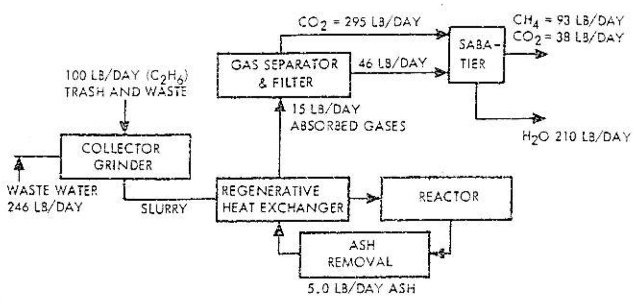
The processing of trash on board the space base provides another potential ECLSS/RCS integration through the utilization of waste gases generated by processing. Because of the experiments program, however, the gases generated and exhausted overboard must be clean. That is, the waste products cannot contaminate space in the vicinity of experiments. During the course of the study, several ECLSS waste processes were considered(1) (i.e., thermal decomposition, destructive distillation, incineration, wet oxidation, and steam reformation). In general, the exhaust products of decomposition and destructive distillation can be expected to be heavy hydrocarbons that can condense on experiments and contaminate the exterior of the base. Although the incineration and oxidation processes produce clean by-products such as CO_2, CO, and water vapor, they require relatively high resupply weight due to oxygen consumption. The steam reformation process, on the other hand, has by-products of CO_2 and H_2. When these by-products are combined in a Sabatier reactor, the products are water and CH_4, as in the reduction process. The steam reformation process has been used for many years by the petrochemical industry for the production of hydrogen from crude oil and coal.(2) At present, the feasibility of trash processing by steam reformation is being investigated. Results to date appear promising.

A block diagram of the process that might be applied to a space base is shown on Figure 2. The process starts with grinding of processable trash and addition of waste water to form slurry. The slurry is then pumped through a regenerative heat exchanger to the reactor. At this point, the reductions shown occur at approximately 1000 F. The by-products are then passed through an ash filter and ash is separated. The product gases are passed through a gas separator/filter where CO_2 and H_2 are separated and trace gases such as sulphur dioxide (SO_2) and NH_3 are absorbed. The CO_2 and H_2 are reacted in a Sabatier reactor, and CO_2, CH_4, and H_2O are formed. As noted on Figure 2, a waste input typified by C_2H_6 was used which results in insufficient H_2 to react all CO_2 produced.

Figure 2 shows an interesting ECLSS consideration in that waste water is used as input and pure water is achieved from the Sabatier. It would appear that this concept offers a potential for achieving an integrated ECLSS/RCS and waste/water processing if the indicated water loss can be overcome in some fashion.

Trash and Waste Model

During the course of the space base study, preliminary estimates of waste from ECLSS and the crew system were on the order of 150 pounds per day. Of this, 80 pounds appeared to be processable. The waste from the experiments program was estimated at 37 pounds per day, with approximately 20 pounds per day processable. In addition to trash, the experiments program could require water at an estimated rate of 216 pounds per day. Of this amount, pounds



* REACTOR REACTIONS

1. $C_nH_{(2n+2)} + n\,H_2O \rightarrow n\,CO + (2n+1)\,H_2$
2. $C_nH_2n + 2 + 2n\,H_2O \rightarrow n\,CO_2 + (3n+1)\,H_2$
3. $CO + H_2O \rightarrow CO_2 + H_2$

Figure 2. Steam Reformation Waste Processing

per day were compatible with normal spacecraft water recovery; 96 pounds per day were considered incompatible with normal recovery because of unusual contamination. For an additional source of water, a wet fecal collection system was considered that produced 150 pounds of fecal water slurry per day.

With these trash and water quantities, the second reaction of Figure 2 was utilized to develop the gross mass and flow balance indicated. This indicates that with 100 pounds of trash and 246 pounds of waste water (experiment and fecal collection system), 210 pounds of fresh water, 93 pounds of CH_4, and 38 pounds of CO_2 could be obtained on a daily basis. This amount of CO_2/CH_4 used in a resistojet at a specific impuse of 185 pound-second per pound would provide 4.36×10^{-6} pound-second impulse in 180 days, virtually eliminating propellant resupply.

The results given above indicate a tremendous potential. It must be emphasized, however, that the concept is still in the feasibility stage as applied to trash-water processing in a space vehicle. There may be significant differences between the trash and waste water availability assumed above and that which may actually exist.

Resistojet Operational Modes

Under normal operating conditions, the CH_4/H_2 mixture from the ECLSS is available from the Sabatier unit at a continuous fixed flow rate and pressure. Therefore, two modes of resistojet operation utilizing these gases are possible: (1) a continuous firing which could be used to counteract the vehicle drag and maintain constant orbit altitude and (2) periodic firings to desaturate the control moment gyros and/or correct the orbit altitude. The latter case requires intermediate storage of the waste gases.

Continuous Operation

The continuous operating mode has the advantage of not requiring intermediate storage and the associated compression requirements to keep the accumulator volumes within reasonable bounds. Very low gravity levels for low-gravity experimentation may also be provided, if required, by offsetting vehicle drag forces with resistojet thrustors operating continuously. Since the drag force in earth orbit varies considerably over a 10- to 11-year cycle, depending on solar activity, the resistojet thrustor must have variable-thrust capability for the continuous operation mode. This may be accomplished in one of two ways without changing the resistojet hardware:

1. The resistojet inlet pressure can be controlled to govern the thrust level while maintaining the thrustor gas temperature to obtain the maximum specific impulse. During low-drag periods, this requires storage of the excess gas or venting through nonpropulsive vents.

2. In conjunction with inlet pressure control, the power to the thrustor can be varied to change the specific impulse, so that all of the gases available are used to counteract the drag forces. This option has the advantage of requiring less power than Option 1.

The continuous operating modes require a more complex control mechanism than the intermittent mode. Both require variable pressure and gas temperature in the resistojet. The resistojet control mechanism must be governed to null the acceleration forces of the vehicle. This requires very precise accelerometers, since the drag acceleration may be on the order of 10^{-7}g or less. Therefore, the continuous operational mode is recommended only if very low acceleration levels are required. Of the two continuous modes, the first is preferable if other functions such as CMG desaturation are to be done with the biowaste resistojet system. The second mode would be preferable only if power usage was a consideration.

Intermittent Operation

The primary design considerations for intermittent operation of the biowaste resistojet system are the sizing of accumulators and engine thrust size. Both are functions of the duty cycle (engine-on time/total time) and the total impulse to be delivered. The accumulators are sized to meet the maximum duty cycle (longest continuous on time). The engine thrust is sized to the minimum duty cycle (minimum on time to accomplish a given total impulse).

For the small duty cycles that normally size the thrustor, the thrustor flow rates are much larger than the continuous flow rate of the biowaste gases from the ECLSS. Therefore, when the thrustors are operating, the accumulators are in a blow-down mode. Figure 3 shows the ratio of accumulator weight to maximum total impulse in a single firing as a function of tank blow-down pressure ratio for the isentropic case.

Conclusions

The following conclusions are made relative to the integration of the ECLSS/RCS of a space base for utilization of biowaste gases for propulsion functions:

1. Utilization of the methane waste gas from the ECLSS oxygen-recovery system in a low-thrust resistojet system significantly reduces the total system fixed weights and consumable resupply.

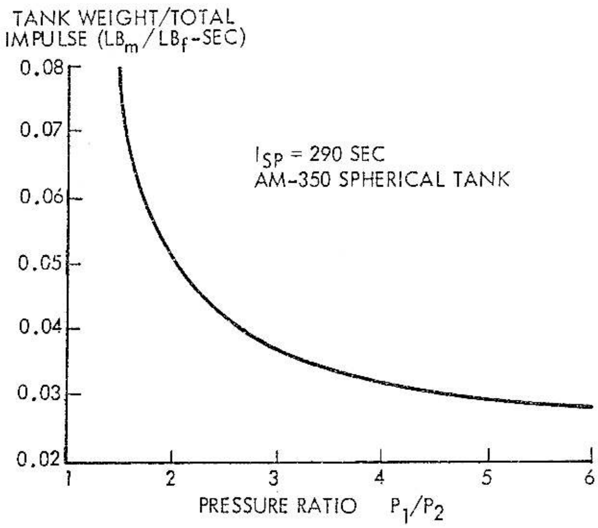


Figure 3. Tank Weight Per Impulse

2. Further ECLSS/RCS integration to provide fuel for a medium-thrust RCS results in only a slight reduction in resupply weight. However, if a water electrolysis concept is used for the medium-thrust RCS, the reduction in mixture ratio of an integrated system could increase engine life because of lower combustion temperatures.

3. Trash processing to produce waste gases for a resistojet has great potential but requires additional testing and studies of the operational impacts.

4. The intermittent operation of the biowaste resistojet is preferred over continuous operation unless very low accelerations levels (less than 10^{-7}g) are required for experimental purposes.

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-- NOTES --